Annex 2

Grid-based model: days of grow-out to a harvestable weight for Atlantic salmon among four salmon-producing countries

João Gomes Ferreira
Department of Environmental Sciences and Engineering
Faculty of Sciences and Technology
New University of Lisbon (Universidade Nova de Lisboa)
Portugal

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Introduction

The objective of this annex is to illustrate the use of a dynamic grid[9]-based growth model to compare the duration of grow-out of Atlantic salmon at four locations in four of the major salmon-producing countries (Canada, Ireland, Kingdom of Norway and the Republic of Chile). The ultimate aim is to improve estimates of the potential for offshore mariculture by integrating the spatial analytical capabilities of a geographic information system (GIS) with farm-based modelling of variables affecting mariculture sustainability.

The vector[10] approach used in this technical paper (Annex 1) resulted in areas with potential identified by establishing a threshold range of temperatures for favourable grow-out and then locating the areas that have a 95 percent probability of being in that range throughout the year. In this approach, a range of temperatures (thresholds) over large areas were used, and it was assumed that the results would be homogeneous for growth throughout those areas. This is unlikely to be the case. By employing a grid-based approach, there would be much less spatial ambiguity about the conditions in that grid cell's relatively small area, and the actual conditions in that grid cell could be investigated by a simple query. The model could be run in any area of interest within a nation's exclusive economic zone to identify geographically related mariculture development advantages. This is a first step towards that goal specifically aimed at offshore mariculture.

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[9] A grid cell (or pixel) is the smallest unit of information in GIS raster data, usually square in shape. In a map or GIS data set, each grid cell represents a portion of the earth, such as a square metre or square mile, and usually has an attribute value associated with it, such as soil type or vegetation class. For the present modelling trial, sea surface temperature (SST) at a nominal 4.5 km2 resolution were used and a time step of one month.

[10] A vector is a representation of the world using points, lines and polygons. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

Methodology

The growth performance of individual salmon was determined by means of a net energy balance model driven by sea surface temperature (SST). The individual growth model developed by Stigebrandt (1999) for growth of Atlantic salmon in Norwegian fjords was used for simulation. This model is based on a conservation of energy equation (Eq. 1, all terms in cal d^{-1}):

$$\text{(Eq. 1)} \qquad Q_r - (Q_f + Q_N) = Q_s + Q_l + Q_{sda} + Q_g + Q_p$$

Where

Q_r = Energy intake from feeding
Q_f = Energy loss from elimination of faeces
Q_N = Energy loss from nitrogen excretion
Q_s = Energy loss from metabolism
Q_l = Energy loss from locomotion
Q_{sda} = Energy loss from apparent specific dynamic action
Q_g = Energy apportioned to growth
Q_p = Energy loss from reproduction

Two of these terms are not explicitly considered. Q_l is considered to be low in inshore culture and is simulated through a small increase in Q_s, and Q_p is inapplicable because animals are harvested prior to reproduction. The change in biomass W with time t is expressed as:

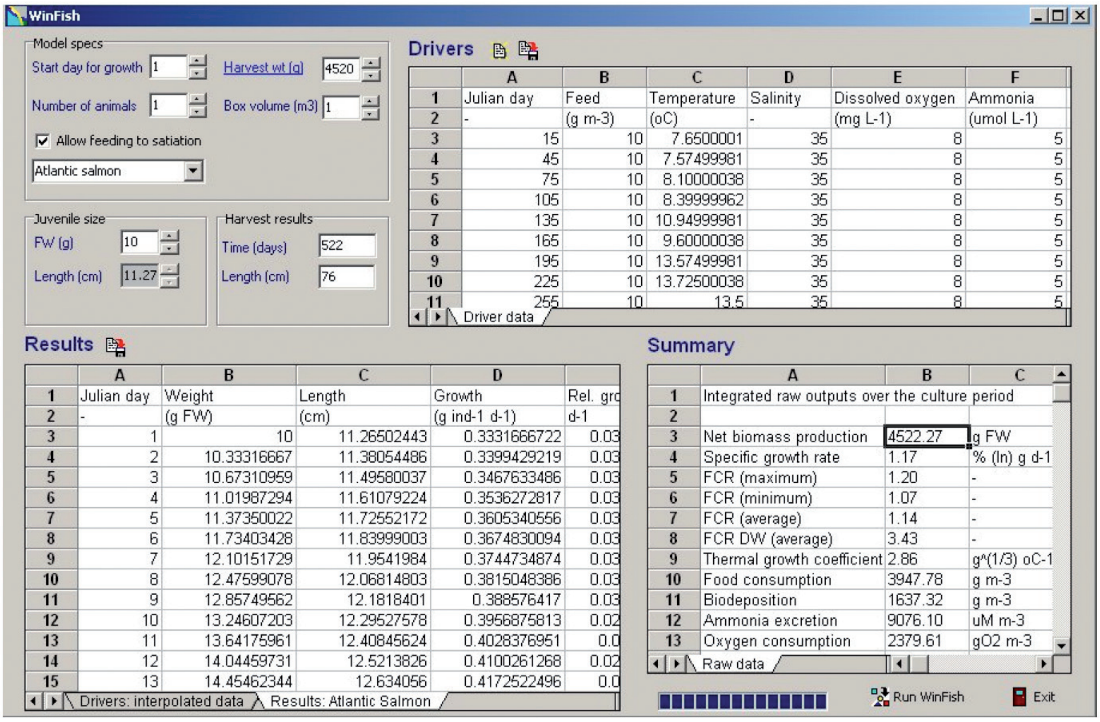
$$\text{(Eq. 2)} \qquad \frac{dW}{dt} = \frac{Q_g}{C_{fi}}$$

Where

C_{fi} = energy per unit mass of salmon (cal g^{-1})

The model was implemented in C++ and can simulate growth under both food satiation conditions and food limitation, considering multiple fish growing in a control volume. Water temperature and food concentration data are used to force the model.

FIGURE A2.1
Screenshot of the WinFish aquaculture modelling software



Start day for growth: 1
Harvest wt (g): 4520
Number of animals: 1
Box volume (m3): 1
☑ Allow feeding to satiation
Atlantic salmon

FW (g): 10
Length (cm): 11.27

Time (days): 522
Length (cm): 76

	A	B	C	D	E	F
1	Julian day	Feed	Temperature	Salinity	Dissolved oxygen	Ammonia
2	-	(g m-3)	(oC)	-	(mg L-1)	(umol L-1)
3	15	10	7.6500001	35	8	5
4	45	10	7.57499981	35	8	5
5	75	10	8.10000038	35	8	5
6	105	10	8.39999962	35	8	5
7	135	10	10.94999981	35	8	5
8	165	10	9.60000038	35	8	5
9	195	10	13.57499981	35	8	5
10	225	10	13.72500038	35	8	5
11	255	10	13.5	35	8	5

	A	B	C	D	
1	Julian day	Weight	Length	Growth	Rel. gr
2	-	(g FW)	(cm)	(g ind-1 d-1)	d-1
3	1	10	11.26502443	0.3331666722	0.03
4	2	10.33316667	11.38054486	0.3399429219	0.03
5	3	10.67310959	11.49580037	0.3467633486	0.03
6	4	11.01987294	11.61079224	0.3536272817	0.03
7	5	11.37350022	11.72552172	0.3605340556	0.03
8	6	11.73403428	11.83999003	0.3674830094	0.03
9	7	12.10151729	11.9541984	0.3744734874	0.03
10	8	12.47599078	12.06814803	0.3815048386	0.03
11	9	12.85749562	12.1818401	0.388576417	0.03
12	10	13.24607203	12.29527578	0.3956875813	0.02
13	11	13.64175961	12.40845624	0.4028376951	0.0
14	12	14.04459731	12.5213826	0.4100261268	0.02
15	13	14.45462344	12.634056	0.4172522496	0.0

	A	B	C
1	Integrated raw outputs over the culture period		
2			
3	Net biomass production	4522.27	g FW
4	Specific growth rate	1.17	% (ln) g d-1
5	FCR (maximum)	1.20	-
6	FCR (minimum)	1.07	-
7	FCR (average)	1.14	-
8	FCR DW (average)	3.43	-
9	Thermal growth coefficient	2.86	g^(1/3) oC-1
10	Food consumption	3947.78	g m-3
11	Biodeposition	1637.32	g m-3
12	Ammonia excretion	9076.10	uM m-3
13	Oxygen consumption	2379.61	gO2 m-3

The modelling software (WinFish – Figure A2.1) allows either growth for a specific period or up to a user-defined weight to be used as model endpoints. WinFish (Ferreira, Saurel and Ferreira, 2012) is a generic package that currently allows simulation of growth for Atlantic salmon, gilthead bream and tilapia.

Salmon farms from Canada (British Columbia), Ireland, the Kingdom of Norway and the Republic of Chile were selected using expert knowledge, and monthly SST profiles were obtained from an SST climatology (Annex 1, Table A1.1) originally based on satellite remote sensing. These profiles were then used in WinFish, which executes a linear interpolation to provide daily water temperatures as inputs to the individual growth model. A harvest weight endpoint of 4 520 g based on the bioeconomic model developed by Jin (2008) was imposed, one individual was fed to satiation, and the total duration of the growth period required to reach the target weight was determined. The equations in the Stigebrandt model also allow the calculation of relevant environmental data. WinFish provides outputs for these at the management level (bottom line), e.g. total fish biomass, cultivation time, production of ammonia, faeces and oxygen consumption (Figure A2.1 – summary pane). More detailed spreadsheets of daily model outputs are also available (Figure A2.1 – results pane), designed to support scientific interpretation of the results obtained.

Results

Table A2.1 shows the averaged model results at the various locations. Averages are shown because the difference among regions is far greater than differences among farms in the same region (within-region coefficient of variation < 10 percent in all cases).

TABLE A2.1

Management-level synthesis of growth simulations in the four geographic areas

Parameter/region	Ireland	Norway	Chile	Canada
Number of farms	7	6	5	6
Growth period (days)	480	578	431	522
Coefficient of variation across farms (%)	2.77	2.29	7.57	5.05
Biomass (g FW)	4 529	4 535	4 539	4 536
Length (cm)	76	76	76	76
Specific growth rate (% (ln) g d^{-1})	1.28	1.06	1.43	1.17
FCR (maximum)	1.20	1.20	1.20	1.20
FCR (minimum)	1.07	1.07	1.07	1.07
FCR (average)	1.14	1.14	1.14	1.14
FCR DW (average)	3.43	3.42	3.43	3.43
Thermal growth coefficient (g1/3 °C^{-1})	2.84	3.05	2.76	2.88
Food consumption (g m^{-3})	3 944	3 956	3 961	3 953
Biodeposition (g m^{-3})	1 636	1 641	1 643	1 640
Ammonia excretion (uM m^{-3})	9 066	9 084	9 108	9 090
Oxygen consumption (g O2 m^{-3})	2 377	2 382	2 388	2 383

Note: DW = Dry weight; FCR = food conversion ratio; FW = Fresh weight.

Because food limitation and photoperiod are not considered in these results, growth is fundamentally determined by SST and allometry. The fastest mean growth was observed in the Republic of Chile (431 days), and the slowest in the Kingdom of Norway with a mean of 578 days, 34 percent longer. The overall spread was between 395 days (the Republic of Chile) and 591 days (the Kingdom of Norway). The endpoint for biomass corresponds to the simulated weight at the first time step beyond the target weight, and has a maximum error of less than 0.5 percent. The results shown in Table A2.1 were indirectly validated through the application of Eq. 3, which allows the determination of total growth time (T) on the basis of the food conversion ratio (FCR), and the feeding rate (FR) taken from industry tables (Stead and Laird, 2002).

(Eq. 3) $$T = \frac{FCR\ (\ln\ end\ weight - \ln\ start\ weight)}{FR} * 100$$

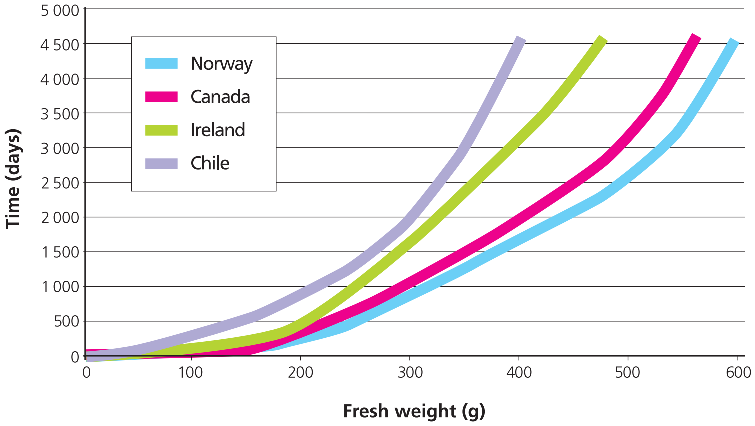
T for the Norwegian sites (mean temperature = 8.5 °C) equates to an FR value of 0.9 to 0.8 (as percent body weight day^{-1}) for a 1 500 g fish, which, using the mean FCR from Table A2.1, gives a value for T of 547–616 days. A similar test for the Republic of Chile farms, with an FR value of 1.05 (mean SST: 11.9oC) gives T = 469 days.

The faster growth (Figure A2.2) is reflected in a higher mean specific growth rate in the Republic of Chile. The thermal growth coefficient (TGC) depends on both the temperature profile and duration of growth, as it uses the integral of daily temperatures over the cultivation period. The TGC is roughly identical for all regions except for the Kingdom of Norway, where it is roughly 10 percent higher, suggesting a better use of thermal energy. However, because this is an externality, there does not seem to be a particular advantage from this higher value. In any case, Stigebrandt (1999) notes that TGC will not be constant for the range of temperatures observed in Norwegian waters and that the TGC model should therefore be used with great caution.

The FCR is identical at all sites, and is typical of salmon aquaculture. Although FCR is usually expressed as a ratio of dry food mass to wet animal weight, Table A2.1 also presents these data in equivalent dry weight units, indicating that the fish production is around 30 percent of the total feed. Data for environmental variables integrated over the culture period are shown in the last four rows of Table A2.1. The values are essentially identical, which would be expected given the use of a target weight as the simulation endpoint. However a shorter production period has a potentially greater impact on the environment, as the rate of biodeposition, excretion of ammonia or oxygen consumption is higher. This needs to be considered in the light of higher SST, which additionally reduces the solubility of oxygen and promotes higher benthic metabolism, thus exacerbating negative impacts of cultivation. For the shortest cultivation period (the Republic of Chile), a single fish in a 1 m^3 volume consumes about 5 mg L^{-1} of dissolved oxygen (DO) per day, which requires an appropriate throughput of DO to successfully support cage culture.

FIGURE A2.2

Growth profiles at selected farms from each geographic area



Discussion

At first glance, the results are striking. They show an approximate five-month difference in the time required to reach a harvestable size between the Republic of Chile and the Kingdom of Norway. That would translate into a sizeable difference yield and in potential gross sales based on the (apparent) same capital investment in culture facilities between these locations. However, other factors such as effects of day length on feeding rates (e.g. Smith *et al.*, 1993) also have to be taken into account.

The inclusion of this salmon individual model in farm-scale models such as MOM (Ervik *et al.*, 1997; Stigebrandt, 1999) or FARM (Ferreira, Hawkins and Bricker, 2007; Ferreira *et al.*, 2009) allows such impacts to be examined at the appropriate scale of cultivation. FARM additionally provides a means to examine the environmental and production trade-offs of combining salmon and bivalve filter feeders, such as oysters or mussels, in integrated multitrophic aquaculture.

This simulation has already been carried out for other species, i.e. for combinations of gilthead bream and Pacific oyster, and required the development of a finfish model that addresses the growth response of fish to water current speed. Past a certain threshold, the metabolic costs of swimming (or opposing current in a moored cage) make aquaculture unviable. On the other hand, the simulated co-cultivation of fish and shellfish suggests that it is possible to use organic matter from finfish culture to cultivate shellfish in open ocean areas where the natural food supply would be insufficient for commercial growth.

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